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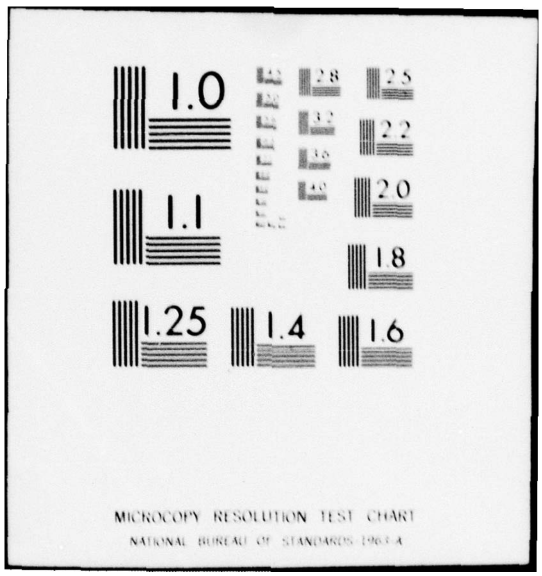
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PREDICTING PROTON SPECTRA
AND RIOMETER ABSORPTION FROM
AND THEORETICAL MODELLING FOR
U-SHAPED SOLAR FLARE RADIO BURSTS.

Pradip Bakshi
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Boston College
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February 1978

Final Report for the Period July 1975 to September 1977.

Approved for public release; distribution unlimited

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Riometer Absorption	Predicting Riometer Absorption	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(1) A practical scheme for using Solar Radio Burst Data of U-shaped spectra to predict the slope as well as the magnitude of the associated proton spectra has been developed, based on empirical correlation studies. (2) A prediction scheme for riometer absorption, using proton spectral parameters as the input has been developed. (3) Theoretical studies relate the source electron distribution parameters to those of the radio spectra, based on the model that the U-shaped spectra originate from a single group of mildly relativistic electrons. These electron-radio results are in qualitative agreement with the empirical proton-radio correlations.

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FOR CONTRACT

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Co-Principal Investigator

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The scope of work under this contract included the following topics:

I. Prediction of the proton energy spectrum from the radio burst spectral data.

II. Correlations between proton energy spectra and the riometer absorption.

III. Theoretical studies on radio spectra and particle distributions associated with solar flares.

I. Prediction of the Proton Energy Spectrum from the Radio Burst Spectral Data

The importance of solar flare radio spectra as predictors of significant proton events was recognized a decade ago at AFGL. The original studies dealt with the basic criterion (U-shaped radio spectrum) which indicates with a high degree of probability the occurrence of a proton event. To obtain a quantitative prediction of the proton spectrum, one has to predict the magnitude, as measured by the proton peak flux at some convenient energy channel (e.g. $E > 10$ MeV) and the slope, which provides the relative intensities of the proton peak fluxes at various energies. Both these questions were addressed here empirically as described below, utilizing the radio burst spectral data as the input, and leading to a quantitative prediction scheme for the full proton spectrum.

A. Prediction of the Proton Spectral Slope

It was established in earlier studies by Bakshi and Barron[1,2] that the width of the U-shaped radio burst is well correlated with the proton spectral slope: wider U's lead to shallow slopes and narrower U's lead to steeper slopes. In the present study, the entire data base, for proton events and for radio bursts, for the period 1966-1973 was carefully scrutinized. The selection criteria were reexamined and further refined. This resulted in the inclusion of some additional events, and modification of some of the earlier data; the final data now represent a more thorough coverage and a greater internal consistency.

In particular, the following problems were encountered, and resolved (as described in detail in the Quarterly Status Reports): For the Radio Data, (1) The consistency of peak flux values from different observatories, when differing values were obtained at neighboring frequencies. (2) The allowable time spread between the peak-times at various frequencies. (3) Using synchronous U's rather than peak flux U's, when detailed time development is available. (4) Handling peak flux spectrum profiles not having smooth shapes. For the Proton Data, (1) Resolving compound events, which involved proper subtraction of the background intensity, when a preceding event had not subsided fully, and scrutinizing the time alignment of the peak fluxes in the three energy channels. (2) Saturation problem for some energy channels in the pre-Explorer data. (3) Consistent use of non-standard channels for the pre-Explorer data. Achieving consistency was a time consuming effort, since the entire data base had to be reexamined in the light of each modification or refinement.

The final results are presented in a journal article being submitted[3] to the Journal of Geophysical Research. The proton (integral) spectral slope β is correlated with the radio width parameter $x = \log(\omega_3/\omega_2)$, where ω_3 is the peak frequency of the high frequency branch of the radio-U and ω_2 is a measure of the cut-off frequency of the lower branch of the U, obtained in three different ways - intercept: ω_2, intersection: ω_2' and observed minimum: ω_2''. Three different functional forms were employed to represent the data - straight line, power-law and exponential. The power-law consistently gave the best correlations for each definition of ω_2. There was no difference between the correlations based on ω_2 or ω_2', and even with ω_2'' the result was not significantly lowered. Thus the directly observed minimum ω_2'' could be used for prediction purposes. The level of correlations ($r \approx 0.77$) is not significantly altered by slight changes in the selection criteria. Thus there appears to be some valid relationship between the proton spectral slope and the 'width' of the radio-U. We find the slope β is well represented by:

$$\beta = \frac{1.185}{(\log_{10}(\omega_{3}, \text{[illegible]}))^{1.01}}$$

In summary, a practical scheme for predicting the proton spectral slope has been developed, using the real time radio data. Furthermore, this empirically established relationship between the proton and radio parameters can now be used as a criterion in judging the relative merits of various theories for radiation processes and particle acceleration in flares.

B. Prediction of Proton Peak Flux Magnitudes

Earlier correlation studies on this topic were based on using time integrated radio flux at a given frequency (Straka and Barron[4], Straka[5]), or 'flash-phase' integrated radio flux at a given frequency (Newell[6]) as the radio parameter, and I_{10}, the peak flux of protons with energies greater than 10 MeV, as the proton parameter. The success of our studies on the proton spectral slope correlations (Bakshi and Barron[1,2]) suggested that more detailed relationships might prevail between the radio and proton parameters and a systematic effort to develop better correlate-variables might prove fruitful. Such a study was carried out, and various new radio and proton correlate-variables were considered, leading to possibly improved prediction schemes for the proton peak flux magnitudes, and a better understanding of the correlation phenomena.

We restricted our data base to the events acceptable for the proton spectral slope study[1-3] so that the full magnitude as well as spectral profile information is available for the radio and proton events. On physical grounds, the 'total' energy in the radio burst and the 'total' energy in the proton event might be expected to be better correlated than the measures used in the past. Thus for the radio data, we considered besides the time integrated fluxes $\bar{I}(\omega)$ at the five individual frequencies (606, 1415, 2695, 4995 and 8800 MHZ), the frequency integrated fluxes $\int \bar{I}(\omega)d\omega$ over the interval (i) 606 to 8800, or (ii) ω_2'' to ω_3, or (iii) the entire available range of frequencies of observation for a given event. Also, the time integration range was restricted to the duration of the U-event. This is a point of departure from earlier studies, and led to significant improvement of correlations at lower frequencies. For the proton data, we considered besides I_{10}, the additional variables (i) $I_{10}\rho_1$ which represents the net energy content rather than just the number of particles, (ii) $I_{10}\tau$, where τ is the duration of the proton event, (iii) $I_{10}\rho_1\tau$ which is a measure of the total energy over the whole duration, and (iv) applied a solar longitudinal correction in each case to correct for the propagational loss. This last factor led to a very significant improvement in correlations.

The complete results, and their implications are presented in the Scientific Report No. 2 (Bakshi and Barron[7]).

By combining our results in A and B above, we now have a practical prediction scheme for the full proton spectrum on the basis of the real time radio burst data.

II. Correlations between the Proton Energy Spectra and the Riometer Absorption.

The riometer absorption is a measure of the ionospheric changes caused by the solar protons, thus a prediction of the former is possible from the knowledge of the complete spectrum of the latter. Empirical connections between riometer absorption and solar protons have been studied for over a decade. Most studies[8-10] have considered a relation of the form $A = mI^{\frac{1}{2}}$ where A is the observed riometer absorption (generally at 30MHZ) and I is the flux of protons with energies greater than some specificed energy. These schemes rely only on the magnitude, and not the slope, of the proton energy spectral profile. It is reasonable to expect that of the two events with the same magnitude I (for protons with energies > 10 MeV), the one with the shallower slope β will produce a larger riometer absorption, since its protons, on the average, carry more energy. Thus a formula which takes into consideration the slope as well as the absolute magnitude of proton profiles can be expected to be more effective.

In Scientific Report No. 1 (Bakshi and Barron[11]), it has been established that using the proton variable $x = \{\log I\ (>10) + \alpha \log \rho\}$, where ρ is a measure of the average energy for the proton flux, and thus depends on the slope β, provides better correlations with the riometer absorption A, than those obtained with the square root type formula. α is an adjustable parameter, and optimizing over α leads to extremely good correlations, with $r \simeq 0.97$! The selection criteria for the choice of events, and other details of the correlation study are described in the Scientific Report No. 1.

In conclusion, we note that the studies described in section I provide a means of predicting the full proton spectrum on the basis of the radio data, and the studies described here, in turn, provide a prediction for riometer absorption from the proton information. Combining these results leads to a direct scheme for the prediction of riometer absorption on the basis of real time radio data.

III. Theoretical Studies on Radio Spectra and Particle Distributions Associated with Solar Flares

The theoretical study of U-shaped solar burst spectra is motivated by the findings of the AFGL Group, which established that a U-shaped radio spectrum predicts with a high probability the occurrence of high energy proton events. In the work of Bakshi and Barron (see section I) the spectral properties of such proton events were studied in detail.

The theoretical work in the contract period was aimed at the completion and extension of our previous works. The basis of our work is an observation made by Kalman and Furutani[12] on the basic emission mechanism of relativistic electrons in an ambient magnetoplasma: it was pointed out that the relativistic electrons can radiate both below and above the electron cyclotron frequency and the radiation in the former range is greatly enhanced by the high refractive index of the magnetoplasma. Further works by Kalman and Yukon,[13] Kalman, Yukon and Bakshi,[14] and Kalman[15] established a model in which the U-shaped spectrum is explained as originating from a single group of electrons. Our theoretical work in the contract period developed in basically two directions. The first line of research was directed at studying the details of the model for a concrete solar scenario. This required, in addition to working out the details of the basic emission mechanism, (i) the consideration of the geometry of the source region in relation to the solar corona; (ii) the study of the detailed longitudinal-transverse conversion mechanism leading to the radiation of electromagnetic modes; and

(iii) the inclusion of gyro-synchrotron self-absorption for the high frequency part of the spectrum. The conclusions of these investigations have been described in a paper[16] submitted to Astrophysical Letters. In that paper a consistent model for U-shaped spectra, based on the originally proposed idea, has been worked out; it has also led to predictions concerning correlations between the parameters of the distribution function of high energy electrons and the parameters of the radio-spectrum. While these predictions (involving the electron distributions) cannot be tested directly, the empirical results of Bakshi and Barron,[1,2] correlating the proton distributions and the radio parameters can be used as a test, if we assume that the electron and proton distributions are similar. Indeed, a qualitative agreement is found to prevail between the empirically established (radio-proton) and the theoretically derived (radio-electron) results. In addition, the theory suggests that the precise radio variable to be used for correlations is $\omega_3/\omega_2^{\lambda}$ (rather than ω_3/ω_2) where $\lambda = 1 - \frac{2}{\beta+5}$, and β is the spectral index of the particle (integral) spectrum. The difference between λ and unity is small, but nevertheless it can be empirically tested by studying whether the use of the predicted value of λ leads to better correlations.

The second line of theoretical research had as its goal, the detailed working out of the particulars of the basic emission mechanism. This work resulted in a paper which is still to be completed in collaboration with Y. Furutani and S. Yukon, which is planned for submission to the Annals of Physics. This paper will discuss the features of the fundamental Chrenkov-synchrotron radiation formula, the question of various divergences and their resolutions, and some problems relating to the effect of the pitch-angle and energy distribution of particles on the emission spectrum.

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1. P. Bakshi and W. Barron; Predicting Riometer Absorption for Solar Bursts. I. Correlations between Proton Spectra and Riometer Absorption, Scientific Report No. 1 AFGL-TR-76-0166, (1976).
2. P. Bakshi and W. Barron; Prediction of Solar Flare Proton Spectral Slope from Radio Burst Data, Journal Article being submitted to Journal of Geophysical Research, (1978).
3. P. Bakshi and W. Barron; Prediction of the Proton Flux Magnitudes from Radio Burst Data, Scientific Report No. 2, AFGL-TR-78-0100, (1978).
4. G. Kalman; A Model for U-shaped Solar Bursts, Journal Article submitted to Astrophysical Letters, (1978).

Abstracts of these publications follow.

1. Scientific Report No. 1

PREDICTING RIOMETER ABSORPTION FOR SOLAR BURSTS.

I. CORRELATIONS BETWEEN PROTON SPECTRA AND RIOMETER ABSORPTION.

Pradip Bakshi and William Barron

June 1976

Abstract

Observed riometer absorption A (in db) is correlated with the proton spectrum variable (log I(>10 MeV) + αlog ρ), where I(>10 MeV) is the peak flux of protons with energies in excess of 10 MeV, ρ is a measure of the average energy of these protons and α is an adjustable parameter. Study of the major proton events (I(>10 MeV) > 100 protons $cm^{-2}sec^{-1}ster^{-1}$) since 1967 shows excellent correlations. Even when the average energy dependent factor is ignored (α=0), our approach provides better correlations than the usual square root relation; optimization over α further improves the correlations to $r \approx 0.97$. A practical program for utilizing solar radio burst data for an early prediction of riometer absorption can now be developed by combining our previous studies on radio → proton correlations with the proton → riometer results reported here.

2. Journal Article, to be submitted to Journal of Geophysical Research

PREDICTION OF SOLAR FLARE PROTON SPECTRAL SLOPE FROM RADIO BURST DATA

Pradip Bakshi and William Barron

Abstract

We have studied the correlations between the width of the U-shaped peak flux density spectra of solar radio bursts and the slope of the associated proton energy spectra, observed by satellites. We find the wider radio-spectra U's lead to shallow proton energy slopes, while narrower U's lead to steeper slopes. Out of the straight line, power-law and exponential forms used to study the correlations, the power-law form yields the best correlation ($r \approx 0.77$). This leads to a real time prediction scheme for forecasting the spectral character of the protons that can be expected to arrive in the vicinity of the earth, on the basis of the continuously monitored radio-burst data.

3. Scientific Report No. 2

PREDICTION OF THE PROTON FLUX MAGNITUDES FROM RADIO BURST DATA.

Pradip Bakshi and William Barron

Abstract

Various radio-burst and proton spectral parameters are considered as correlation variables to develop an improved prediction scheme for the proton peak flux magnitudes. Besides the time integrated radio fluxes at individual frequencies, we also use a frequency integration over three different ranges. For the protons, we have considered besides the peak flux of protons (with energy greater than 10 MeV) their average energy and their duration, and also applied a solar longitudinal correction. Our results lead to an improved prediction scheme and provide a better understanding of the correlation phenomana.

4. Journal Article, submitted to Atrophysical Letters.

A MODEL FOR U-SHAPED SOLAR BURSTS

G. Kalman

January 1978

Abstract

We present a model for U-shaped solar burst spectra in terms of one single group of radiating mildly relativistic electrons. The low-frequency band is due to radiation into the electronic (Whistler) mode of the ambient plasma, while the high frequency band is basically self-absorbed vacuum synchrotron radiation. The predominantly longitudinal low-frequency radiation is converted into transverse radiation by incoherent scattering on dressed thermal ions. The model predicts correlations between the position of the high frequency cut-off of the low-frequency band, the peak frequency of the high-frequency band and the energy spectrum of the high energy electrons. Contact is made with recent empirically established similar correlations for high energy protons.